

Residential and Industrial Worker Risks from Soil and Groundwater Vapor Intrusion Into Buildings

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Summary

Volatilization of chemicals of concern (COCs) present in soil and groundwater and their subsequent intrusion into enclosed spaces constitutes a potential inhalation exposure pathway; hence, a potential health risk to the occupants (USEPA, 1997). CPCPRC used the Johnson and Ettinger (*J&E*) model to assess the potential risk to onsite receptors and the industrial workers on the adjoining AES property.

The evaluated onsite receptors consisted on an office or industrial worker and a hypothetical resident. The AES receptors consisted of an office worker in the AES administration building and a worker in the AES shed near the southwestern CPCPRC property boundary.

Site-specific soil properties and exposure parameters were used where available. In the absence of site-specific inputs, the conservative model defaults were used. Vapor intrusion modeling was performed for the volatile and semi-volatile chemicals and mercury detected in the Area of Concern (AOC) Investigation soil samples and the May/June 2012 comprehensive groundwater samples.

During the AOC Investigation 259 surface soil and 259 subsurface soil samples were collected. Additionally, 55 Upper Alluvial wells and 23 Lower Alluvial wells were sampled in May – June 2012. Most of these wells were sampled again in December 2012.

It was conservatively assumed that the volatilization would occur from all sampled media. Therefore, the data for the surface soil and subsurface soil were combined and the data for the lower aquifer and the upper aquifer were combined. From these data, statistically derived exposure point concentrations (EPCs) that would be representative of the site-wide media were calculated. This approach recognizes that a residential or industrial building could be built anywhere on the site. The EPCs were calculated using the EPA's ProUCL Version 4.1 software. The details of EPC derivation are provided in the main body of the report.

The onsite receptors were evaluated separately for risk from soil and groundwater and the risks from the two media were also added. The two AES receptors were evaluated only for risk from groundwater as the soil contamination is contained within the CPCPRC property boundary and only the groundwater plume is known to have migrated beneath the AES property.

The EPCs were used in the forward, quantitative risk calculations. Risks were calculated for the detected volatile and semivolatile organic compounds, and mercury which are built into

the *J&E* model. The risks are expressed as incremental lifetime cancer risk (ILCR) for carcinogenic chemicals and as hazard index (HI) for non-carcinogenic chemicals. The benchmarks used to determine the acceptability of the individual chemical risks are: ILCR no greater than 1×10^{-6} (i.e., one cancer incidence per one million persons) and HI no greater than 1. The ILCR up to 1×10^{-4} (1 cancer incidence per 10,000 persons) may be acceptable as total risk from all chemicals, on a site-specific basis. The vapor intrusion risks for the four receptors are summarized below and are detailed in Table 1a (onsite Resident), Table 1b (onsite Industrial Worker), Table 1c (AES Administration Worker) and Table 1d (AES Shed Worker).

Receptor	Media	Total ILCR	Total HI
Onsite Resident (Table 1a)	Soil and Groundwater	8.E-04	8.E+00
Onsite Worker (Table 1b)	Soil and Groundwater	2.E-04	2.E+00
AES Administration Worker (Table 1c)	Groundwater	3.E-05	4.E-01
AES Shed Worker (Table 1d)	Groundwater	4.E-05	4.E-01

ILCR = Incremental lifetime cancer risk; HI = hazard index

Table 1a. Summary of onsite residential risks from indoor vapor intrusion.

Analyte	GW Unit	GW EPC	SO Unit	SO EPC	GW ILCR	GW HI	SO ILCR	SO HI	Total ILCR	Total HI
1,2-Dichlorobenzene	ug/L	0.938	-	-	NA	1.E-05	-	-	-	1.E-05
1,2-Dichloroethane	-	-	ug/Kg	4.742	-	-	1.E-06	2.E-02	1.E-06	2.E-02
1,4-Dichlorobenzene	ug/L	1.518	-	-	2.E-08	3.E-05	-	-	2.E-08	3.E-05
Acenaphthene	ug/L	0.446	-	-	NA	2.E-06	-	-	-	2.E-06
Acetone	ug/L	46	ug/Kg	1521	NA	1.E-04	NA	5.E-03	-	5.E-03
Benzene	ug/L	11469	ug/Kg	2995	2.E-04	2.E+00	2.E-04	2.E+00	4.E-04	4.E+00
Benzo(b)fluoranthene	ug/L	0.3	ug/Kg	44.81	9.E-09	NA	4.E-10	NA	9.E-09	0.E+00
Chlorobenzene	ug/L	2.902	-	-	NA	2.E-04	-	-	-	2.E-04
Chloroform	ug/L	10	-	-	4.E-07	1.E-02	-	-	4.E-07	1.E-02
Chrysene	ug/L	0.31	-	-	9.E-10	NA	-	-	9.E-10	0.E+00
Ethylbenzene	ug/L	870.4	ug/Kg	19216	5.E-06	4.E-03	4.E-04	4.E-01	4.E-04	4.E-01
Fluorene	ug/L	5.24	-	-	NA	2.E-05	-	-	-	2.E-05
Mercury	ug/L	0.135	ug/Kg	28.71	NA	1.E-03	NA	7.E-02	-	8.E-02
Methyl tert-butyl ether	ug/L	2.76	ug/Kg	6.89	7.E-10	2.E-06	1.E-08	4.E-05	1.E-08	4.E-05
m-Xylene & p-Xylene	ug/L	2676	-	-	NA	2.E-02	NA	3.E+00	-	3.E+00
Naphthalene	ug/L	17.52	ug/Kg	249	4.E-07	8.E-03	2.E-06	4.E-02	2.E-06	4.E-02
Nitrobenzene	ug/L	8.4	ug/Kg	1500	9.E-08	3.E-03	9.E-06	3.E-01	1.E-05	3.E-01
o-Xylene	ug/L	697	ug/Kg	17124	NA	4.E-03	NA	5.E-01	-	5.E-01
Pyrene	ug/L	0.62	-	-	NA	1.E-06	-	-	-	1.E-06
Styrene	-	-	ug/Kg	569	-	-	NA	3.E-03	-	3.E-03
Tetrachloroethene	ug/L	1.31	-	-	1.E-09	2.E-05	-	-	1.E-09	2.E-05
Toluene	ug/L	152.3	ug/Kg	5184	NA	2.E-03	NA	3.E-01	-	3.E-01
Total					2.E-04	2.E+00	6.E-04	7.E+00	8.E-04	8.E+00

GW = groundwater; SO = soil; EPC = exposure point concentration

ILCR = incremental lifetime cancer risk, HI = hazard index, ; NA = not applicable.

Table 1b. Summary of onsite industrial worker risks from indoor vapor intrusion.

Analyte	GW Unit	GW EPC	SO Unit	SO EPC	GW ILCR	GW HI	SO ILCR	SO HI	Total ILCR	Total HI
1,2-Dichlorobenzene	ug/L	0.938	-	-	NA	2.E-06	-	-	-	2.E-06
1,2-Dichloroethane	-	-	ug/Kg	4.742	-	-	2E-07	5.E-03	2.E-07	5.E-03
1,4-Dichlorobenzene	ug/L	1.518	-	-	3.E-09	8.E-06	-	-	3.E-09	8.E-06
Acenaphthene	ug/L	0.446	-	-	NA	5.E-07	-	-	-	5.E-07
Acetone	ug/L	46	ug/Kg	1521	NA	3.E-05	NA	1.E-03	-	1.E-03
Benzene	ug/L	11469	ug/Kg	2995	4.E-05	4.E-01	5E-05	5.E-01	8.E-05	1.E+00
Benzo(b)fluoranthene	ug/L	0.3	ug/Kg	44.81	2.E-09	NA	8E-11	NA	2.E-09	-
Chlorobenzene	ug/L	2.902	-	-	NA	4.E-05	-	-	-	4.E-05
Chloroform	ug/L	10	-	-	8.E-08	3.E-03	-	-	8.E-08	3.E-03
Chrysene	ug/L	0.31	-	-	2.E-10	NA	-	-	2.E-10	-
Ethylbenzene	ug/L	870.4	ug/Kg	19216	9.E-07	1.E-03	9E-05	1.E-01	9.E-05	1.E-01
Fluorene	ug/L	5.24	-	-	NA	6.E-06	-	-	-	6.E-06
Mercury	ug/L	0.135	ug/Kg	28.71	NA	3.E-04	NA	2.E-02	-	2.E-02
Methyl tert-butyl ether	ug/L	2.76	ug/Kg	6.89	1.E-10	5.E-07	2E-09	9.E-06	3.E-09	9.E-06
m-Xylene & p-Xylene	ug/L	2676	-	-	NA	5.E-03	NA	9.E-01	-	9.E-01
Naphthalene	ug/L	17.52	ug/Kg	249	7.E-08	2.E-03	3E-07	9.E-03	4.E-07	1.E-02
Nitrobenzene	ug/L	8.4	ug/Kg	1500	2.E-08	6.E-04	2E-06	7.E-02	2.E-06	7.E-02
o-Xylene	ug/L	697	ug/Kg	17124	NA	1.E-03	NA	1.E-01	-	1.E-01
Pyrene	ug/L	0.62	-	-	NA	3.E-07	-	-	-	3.E-07
Styrene	-	-	ug/Kg	569	-	-	NA	8.E-04	-	8.E-04
Tetrachloroethene	ug/L	1.31	-	-	3.E-10	5.E-06	-	-	3.E-10	5.E-06
Toluene	ug/L	152.3	ug/Kg	5184	NA	5.E-04	NA	7.E-02	-	7.E-02
Total					4.E-05	4.E-01	1.E-04	2.E+00	2.E-04	2.E+00

GW = groundwater; SO = soil; EPC = exposure point concentration

ILCR = incremental lifetime cancer risk, HI = hazard index, ; NA = not applicable.

Table 1c. Summary of AES administration worker risks from groundwater indoor vapor intrusion.

Analyte	Unit	EPC	Ind ILCR	Ind HI
1,2-Dichlorobenzene	ug/L	0.938	NA	2.E-06
1,4-Dichlorobenzene	ug/L	1.518	3.E-09	8.E-06
Acenaphthene	ug/L	0.446	NA	5.E-07
Acetone	ug/L	46	NA	3.E-05
Benzene	ug/L	11469	3.E-05	4.E-01
Benzo(b)fluoranthene	ug/L	0.3	2.E-09	NA
Chlorobenzene	ug/L	2.902	NA	4.E-05
Chloroform	ug/L	10	8.E-08	3.E-03
Chrysene	ug/L	0.31	2.E-10	NA
Ethylbenzene	ug/L	870.4	9.E-07	1.E-03
Fluorene	ug/L	5.24	NA	6.E-06
Mercury	ug/L	0.135	NA	3.E-04
Methyl tert-butyl ether	ug/L	2.76	1.E-10	4.E-07
m-Xylene & p-Xylene	ug/L	2676	NA	4.E-03
Naphthalene	ug/L	17.52	7.E-08	2.E-03
Nitrobenzene	ug/L	8.4	2.E-08	6.E-04
o-Xylene	ug/L	697	NA	1.E-03
Pyrene	ug/L	0.62	NA	3.E-07
Tetrachloroethene	ug/L	1.31	3.E-10	5.E-06
Toluene	ug/L	152.3	NA	5.E-04
Total			3.E-05	4.E-01

EPC = exposure point concentration

Ind = industrial worker, ILCR = incremental lifetime cancer risk, HI = hazard index, ; NA = not applicable.

Table 1d. Summary of AES shed worker risks from groundwater indoor vapor intrusion.

Analyte	Unit	EPC	Ind ILCR	Ind HI
1,2-Dichlorobenzene	ug/L	0.938	NA	2.E-06
1,4-Dichlorobenzene	ug/L	1.518	3.E-09	8.E-06
Acenaphthene	ug/L	0.446	NA	4.E-07
Acetone	ug/L	46	NA	2.E-05
Benzene	ug/L	11469	4.E-05	4.E-01
Benzo(b)fluoranthene	ug/L	0.3	1.E-09	NA
Chlorobenzene	ug/L	2.902	NA	4.E-05
Chloroform	ug/L	10	8.E-08	3.E-03
Chrysene	ug/L	0.31	1.E-10	NA
Ethylbenzene	ug/L	870.4	1.E-06	1.E-03
Fluorene	ug/L	5.24	NA	4.E-06

Analyte	Unit	EPC	Ind ILCR	Ind HI
Mercury	ug/L	0.135	NA	4.E-04
Methyl tert-butyl ether	ug/L	2.76	1.E-10	5.E-07
m-Xylene & p-Xylene	ug/L	2676	NA	5.E-03
Naphthalene	ug/L	17.52	7.E-08	2.E-03
Nitrobenzene	ug/L	8.4	1.E-08	4.E-04
o-Xylene	ug/L	697	NA	1.E-03
Pyrene	ug/L	0.62	NA	1.E-07
Tetrachloroethene	ug/L	1.31	3.E-10	5.E-06
Toluene	ug/L	152.3	NA	5.E-04
Total			4.E-05	4.E-01

EPC = exposure point concentration

Ind = industrial worker, ILCR = incremental lifetime cancer risk, HI = hazard index, ; NA = not applicable.

The following conclusions can be drawn from Tables 1a to 1d:

- **Onsite Resident** – volatilization from soil and subsequent vapor intrusion is the primary contributor to the inhalation risks; approximately 76% of the carcinogenic risk and 79% of the non-carcinogenic risk arise from soil vapors, while the groundwater vapors contribute approximately 24% and 21% of the total risks, respectively. Benzene and ethylbenzene in soil are the carcinogenic risks drivers, while benzene and m & p-xylenes are the noncarcinogenic risk drivers;
- **Onsite Worker** – volatilization from soil and subsequent vapor intrusion is the primary contributor to the inhalation risks; approximately 80% of the carcinogenic risk and 81% of the non-carcinogenic risk arise from soil vapors, while the groundwater vapors contribute approximately 20% and 19% of the total risks, respectively. Both the carcinogenic and non-carcinogenic risks are slightly above the respective thresholds of ILCR no greater than 1×10^{-4} and HI no greater than 1. Benzene, ethylbenzene and, nitrobenzene are the primary carcinogenic risk drivers. No individual chemical exceeds the HI of 1;
- **AES Administration Worker** – Only groundwater vapor intrusion was applicable to this off-site receptor. The carcinogenic and non-carcinogenic risks are below the respective thresholds of ILCR no greater than 1×10^{-4} and HI no greater than 1. Benzene exceeds the individual chemical threshold of 1×10^{-6} ILCR and contributes 97% of the total carcinogenic risk. No chemical exceeds the HI of 1; and
- **AES Shed Worker** – Only groundwater vapor intrusion was applicable to this off-site receptor. The carcinogenic and non-carcinogenic risks are below the respective thresholds of ILCR no greater than 1×10^{-4} and HI no greater than 1. Benzene exceeds the individual chemical threshold of 1×10^{-6} ILCR and contributes 97% of the total carcinogenic risk. No chemical exceeds the HI of 1.

USEPA's Johnson and Ettinger Model

Johnson and Ettinger (1991) introduced a screening-level model which incorporates convective and diffusive mechanisms for estimating the transport of contaminant vapors emanating from either subsurface soils or groundwater into indoor spaces located directly above or in close proximity to the source of contamination. The United States Environmental Protection Agency (USEPA) has developed a series of spreadsheets that allow for site-specific application of the *J&E* model (USEPA, 1997).

USEPA developed two versions of the *J&E* spreadsheet model, a screening-level version and a second-tier or, advanced version. The screening-level approach employs conservative default values for many model input parameters but allows the user to define values for key variables. The second-tier approach allows the user to define values for all model variables and allows for up to three different soil strata between the top of contamination and the enclosed structure. CPCPRC used the second-tier advanced model (2003 version) to assess vapor intrusion into the structures.

The output of the *J&E* model can be a risk-based groundwater concentration (RBC) if the groundwater concentrations are not available or the quantitative risk if the groundwater concentrations are available. The RBC is the minimum of the following values: the carcinogenic RBC (assuming a 1×10^{-6} target risk level), the noncarcinogenic RBC (assuming a target hazard quotient of 1), and the pure component water solubility. In some cases a COC will not have either a carcinogenic or noncarcinogenic RBC due to the lack of an approved toxicity value (i.e., inhalation slope factor for carcinogens or inhalation reference dose for noncarcinogens) in the USEPA Integrated Risk Information System (IRIS), provisional peer reviewed toxicity value (PPRTV), or Health Effects Assessment Tables (HEAST) databases.

Because the soil and groundwater EPCs were available, RBC calculation was not required and the model was used in the forward quantitative risk calculation mode.

Model Theory

The fundamental theoretical development of this model was performed by Johnson and Ettinger (1991). The Johnson and Ettinger model is a one-dimensional analytical solution to convective and diffusive vapor transport into indoor spaces and provides an estimated attenuation coefficient that relates the vapor concentration in the indoor space to the vapor concentration at the source of contamination. The model is constructed as both a steady state solution to vapor transport (infinite or non-diminishing source) and as a quasi-steady state solution (finite or diminishing source). For this modeling effort, CPCPRC has conservatively assumed an infinite source lies directly beneath the structure.

Chemical fate and transport within soils and between the soil column and enclosed spaces is determined by a number of physical and chemical processes. Inputs to the model include chemical properties of the contaminant, saturated and unsaturated zone soil properties, and structural properties of the building. Johnson and Ettinger (1991) reported that the results of the model were in qualitative agreement with published experimental case histories and in good qualitative and quantitative agreement with detailed three-dimensional numerical modeling of radon transport into houses.

As presently constructed, the soil contamination component of the model operates under the assumption that the initial soil concentration is below the soil saturation concentration (i.e., that a residual or pure component phase does not exist). Likewise, the ground water contamination component of the model assumes that the initial ground water concentration is below the water solubility limit. Because the Johnson and Ettinger model is one-dimensional, the building is assumed to be directly above the contamination. In addition, the model does not consider convective water movement within the soil column, nor does it consider transformation processes (e.g., biodegradation, hydrolysis, etc.).

Model Setting

The Johnson and Ettinger Model considers a contaminant vapor source (see C_{source} in Figure 1) located some distance (L_T) below the floor of an enclosed building constructed with a basement or constructed slab-on-grade. The source of contamination is a volatile contaminant in solution with groundwater below the water table. Figure 1 illustrates the scenario where the source of contamination is below the top of the water table. Here the contaminant must diffuse through a capillary zone immediately above the water table and through the subsequent unsaturated or vadose zone before convection transports the vapors into the structure. The rate of soil gas entry (Q_{soil}) is a function solely of convection; however, the vapor concentration entering the structure may be limited by either convection or diffusion depending upon the magnitude of the source-building separation (L_T).

Modeling Input

CPCPRC's approach to the vapor intrusion modeling was to use site-specific data when available and conservative input parameters as part of a reasonable maximum exposure scenario. In some cases, the use of the maximum values for certain input parameters may overestimate potential exposure via vapor intrusion into buildings.

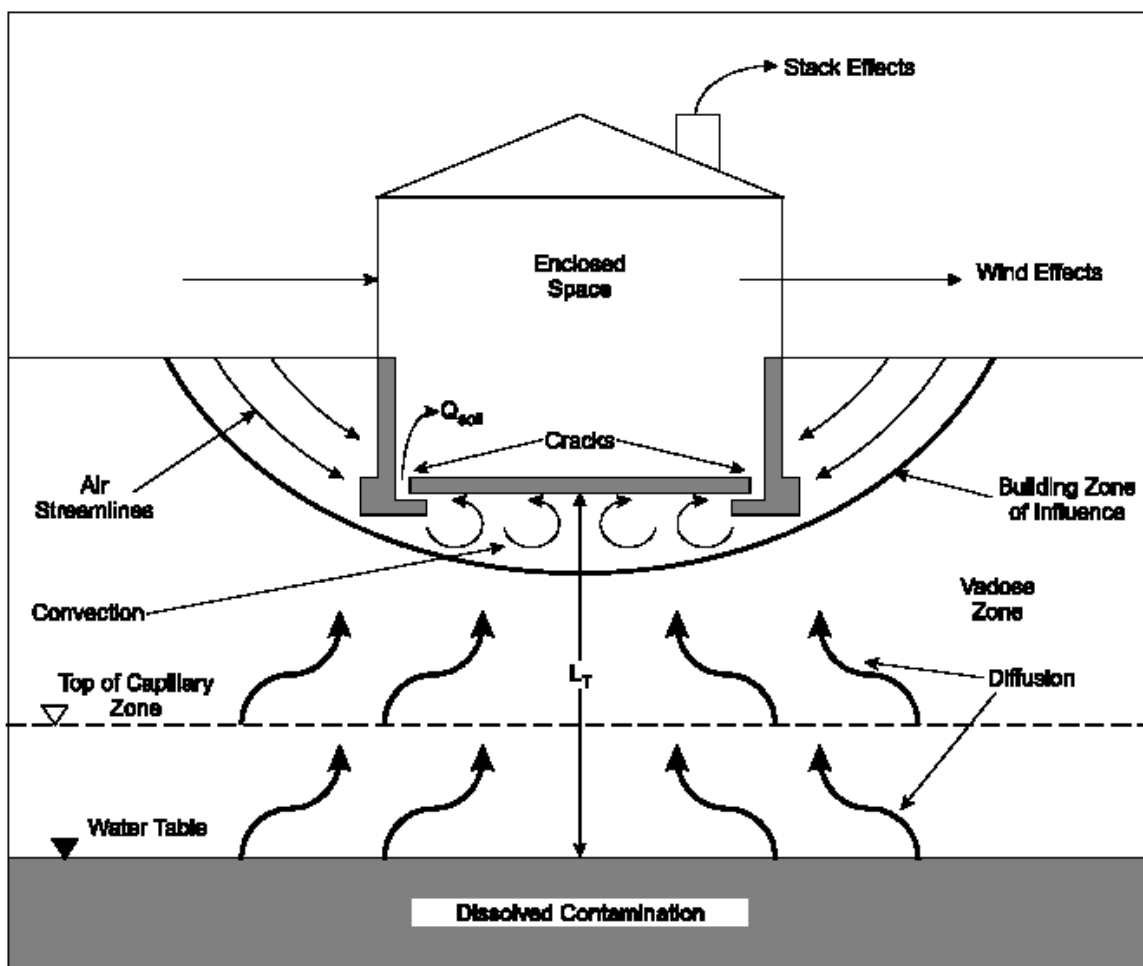


FIGURE 1
Conceptual Model – Vapor Intrusion of Volatile Compounds in Groundwater into Buildings. Adapted from USEPA, 1997.

Site Exposure Areas

The houses in the area are constructed as either slab on grade or are elevated on concrete piers to minimize flooding during storms. The windows of the houses consist of insect screens and louvers. Glass windows are generally not observed. For this modeling effort, it has been conservatively assumed that the standard home is constructed as slab on grade. The home size was assumed to be about 33 feet long and 33 feet wide (1,076 square feet), with 8-foot ceiling and is based on observations of the homes in the area. The same specifications were used for the hypothetical onsite office building on CPCPRC.

The AES administration building is constructed as slab on grade, and is 200 feet long by 50 feet wide, with 8-foot ceiling. The AES shed is 20 feet long by 12 feet wide with an 8-foot ceiling. The shed was constructed on compacted fill estimated to be 8 feet above the historical natural ground surface. Groundwater was assumed to occur 8 feet below natural grade (16 feet below grade for the AES shed).

Table 2a presents the summary statistics for the constituents detected in groundwater, and Table 2b present the summary statistics for constituents detected in soil.

Table 2a. Summary statistics for groundwater samples.

Analyte	CAS	Number of Samples	Number of Detects	Unit	Maximum Detected	EPC	In J&E?
1,2-Dichlorobenzene	95-50-1	78	2	ug/L	1.1	0.94	Y
1,4-Dichlorobenzene	106-46-7	78	3	ug/L	1.9	1.5	Y
Acenaphthene	83-32-9	78	16	ug/L	3.9	0.45	Y
Acetone	67-64-1	78	1	ug/L	46	46	Y
Benzene	71-43-2	132	42	ug/L	190000	11469	Y
Benzo(b)fluoranthene	205-99-2	78	1	ug/L	0.3	0.30	Y
Chlorobenzene	108-90-7	78	9	ug/L	18	2.9	Y
Chloroform	67-66-3	78	1	ug/L	10	10.0	Y
Chrysene	218-01-9	78	1	ug/L	0.31	0.31	Y
Ethylbenzene	100-41-4	132	28	ug/L	14000	870	Y
Fluorene	86-73-7	78	27	ug/L	83	5.2	Y
Mercury	7439-97-6	78	12	ug/L	1.5	0.14	Y
Methyl tert-butyl ether	1634-04-4	123	39	ug/L	27	2.8	Y
m-Xylene & p-Xylene	179601-23-1	132	29	ug/L	39000	2676	Y
Naphthalene	91-20-3	123	37	ug/L	250	18	Y
Nitrobenzene	98-95-3	78	1	ug/L	8.4	8.4	Y
o-Xylene	95-47-6	132	18	ug/L	29000	697	Y
Pyrene	129-00-0	78	2	ug/L	0.63	0.62	Y
Tetrachloroethene	127-18-4	78	2	ug/L	1.5	1.3	Y
Toluene	108-88-3	132	13	ug/L	4500	152	Y
2,4-Dimethylphenol	105-67-9	78	4	ug/L	17	5.7	N
2-Methylphenol	95-48-7	78	2	ug/L	6.1	4.0	N
3 & 4 Methylphenol	15831-10-4	78	7	ug/L	14	1.3	N
Anthracene	120-12-7	78	9	ug/L	8.5	0.64	N
Arsenic	7440-38-2	78	35	ug/L	180	15	N
Barium	7440-39-3	78	78	ug/L	1300	312	N
Benzo(a)anthracene	56-55-3	78	1	ug/L	0.27	0.27	N
Benzo(a)pyrene	50-32-8	78	1	ug/L	0.15	0.15	N
bis(2-ethylhexyl) phthalate	117-81-7	78	3	ug/L	10	3.5	N
Cadmium	7440-43-9	78	3	ug/L	2.1	1.1	N
Chromium	7440-47-3	78	17	ug/L	1800	144	N
Chromium, hexavalent	18540-29-9	78	17	ug/L	24	8.1	N
Cobalt	7440-48-4	78	11	ug/L	19	4.8	N
Copper	7440-50-8	78	35	ug/L	86	7.9	N
Cyanide, Total	57-12-5	78	1	ug/L	3.2	3.2	N
Fluoranthene	206-44-0	78	2	ug/L	0.84	0.54	N
Indeno(1,2,3-cd)pyrene	193-39-5	78	1	ug/L	0.27	0.27	N
Lead	7439-92-1	78	28	ug/L	53	4.1	N
Manganese	7439-96-5	78	78	ug/L	15000	2056	N
Nickel	7440-02-0	78	19	ug/L	450	26	N
Phenol	108-95-2	78	6	ug/L	120	19	N
Selenium	7782-49-2	78	3	ug/L	7.2	4.5	N

Analyte	CAS	Number of Samples	Number of Detects	Unit	Maximum Detected	EPC	In J&E?
Sulfolane	126-33-0	123	90	ug/L	14000	1112	N
Vanadium	7440-62-2	78	35	ug/L	120	12	N
Zinc	7440-66-6	78	18	ug/L	740	42	N

Table 2b. Summary statistics for soil samples.

Analyte	CAS	Number of Samples	Number of Detects	Unit	Maximum Detected	EPC	In J&E?
Acetone	67-64-1	518	223	ug/ Kg	47000	1521	Y
Benzene	71-43-2	518	190	ug/ Kg	170000	2995	Y
Naphthalene	91-20-3	518	36	ug/ Kg	7400	249	Y
o-Xylene	95-47-6	518	187	ug/ Kg	790000	17124	Y
Nitrobenzene	98-95-3	518	1	ug/ Kg	1500	1500	Y
Ethylbenzene	100-41-4	518	199	ug/ Kg	710000	19216	Y
Styrene	100-42-5	518	34	ug/ Kg	24000	569	Y
1,2-Dichloroethane	107-06-2	518	2	ug/ Kg	83	5	Y
Toluene	108-88-3	518	134	ug/ Kg	260000	5184	Y
Benzo(b)fluoranthene	205-99-2	518	14	ug/ Kg	390	45	Y
Methyl tert-butyl ether	1634-04-4	518	37	ug/ Kg	260	7	Y
Mercury	7439-97-6	518	499	ug/ Kg	690	29	Y
m-Xylene & p-Xylene	179601-23-1	518	298	ug/ Kg	5700000	120504	Y
2,4-Dinitrotoluene	121-14-2	518	3	ug/ Kg	450	440	N
7,12-Dimethylbenz(a)anthracene	57-97-6	518	1	ug/ Kg	63	63	N
Antimony	7440-36-0	518	101	ug/ Kg	2400	1159	N
Arsenic	7440-38-2	518	518	ug/ Kg	54000	3774	N
Barium	7440-39-3	518	518	ug/ Kg	330000	101098	N
Benzo(a)anthracene	56-55-3	518	6	ug/ Kg	610	48	N
Benzo(a)pyrene	50-32-8	518	9	ug/ Kg	400	43	N
bis(2-ethylhexyl) phthalate	117-81-7	518	74	ug/ Kg	13000	345	N
Cadmium	7440-43-9	518	390	ug/ Kg	4500	291	N
Chromium, hexavalent	18540-29-9	518	394	ug/ Kg	9800	1887	N
Cobalt	7440-48-4	518	518	ug/ Kg	58000	20122	N
Copper	7440-50-8	518	518	ug/ Kg	710000	82480	N
Cyanide, Total	57-12-5	518	77	ug/ Kg	6400	223	N
Indeno(1,2,3-cd)pyrene	193-39-5	518	9	ug/ Kg	180	39	N
Lead	7439-92-1	518	518	ug/ Kg	210000	12244	N
Manganese	7439-96-5	518	518	ug/ Kg	8300000	974348	N
Nickel	7440-02-0	518	518	ug/ Kg	580000	17261	N
Selenium	7782-49-2	518	190	ug/ Kg	4000	590	N
Silver	7440-22-4	518	93	ug/ Kg	810	212	N
Sulfolane	126-33-0	518	76	ug/ Kg	17000000	247127	N
Vanadium	7440-62-2	518	518	ug/ Kg	260000	123355	N
Zinc	7440-66-6	518	518	ug/ Kg	610000	75541	N

The site-specific soils and building parameters used in the modeling effort are provided in Tables 3 and 4 (see the spreadsheet JE_Tables.xls on the CD). General explanations for the parameters follow:

- Average soil/groundwater temperature (T_s): The soil/groundwater temperature is used to correct the Henry's law constant to the specified temperature. An average groundwater temperature of 27°C is used in the modeling effort and is based on average groundwater temperatures measured during groundwater sampling.
- Depth below grade to base of enclosed space (L_F): The depth to the bottom of the floor in contact with the soil. The USEPA default value for slab on grade construction, 15 cm, was used in the modeling effort.

Depth below grade to water table (L_{wt}) : The depth to the top of the water table (i.e., where the pressure head is equal to zero and the pressure is atmospheric). The thickness of the capillary zone is calculated based on the SCS soil type above the top of the water table. The depth below grade to the top of the water table minus the thickness of the capillary zone must be greater than the depth below grade to the bottom of the enclosed space floor. This means that the top of the capillary zone is always below the floor. The values are specific to each area modeled.

- Soil Stratum Thickness: The thickness of Stratum A must be at least as thick as the depth below grade to the bottom of the enclosed space floor. The combined thickness of all strata must be equal to the depth to the top of contamination or to the top of the water table, as appropriate. At each location where soil data is available, CPCPRC collected soil samples from the 0 to 61 cm interval (0 to 2 feet). Beneath this interval, soil samples were collected at intervals showing obvious signs of contamination or, if no contamination was evident, from directly above the water table at the time of drilling. The average thickness of Stratum B was assumed to be 6 feet. Combined with the thickness of 2 feet for Stratum A, the total soil stratum thickness, or the depth to groundwater of 8 feet was assumed (16 feet for the AES shed).
- SCS Soil Type: The J&E Model provides information for 12 U.S. Soil Conservation Service (SCS) soil types. CPCPRC soil descriptions are based on a separate system, the ASTM Unified Soil Classification System. For this modeling effort, CPCPRC has attempted to best fit the soils described in the field into the SCS soil type provided in the model.
 - Soil Type for Soil Strata
 - Stratum A – Clay (bulk density 1.43 g/cm³)
 - Stratum B – Sandy Clay or SC (bulk density 1.63 g/cm³)

Table 3. Soil properties.

Modeling Parameter	Variable	Units	Value
Average soil/groundwater temperature	T_s	(°C)	27
Depth below grade to bottom of enclosed space floor	L_F	(cm)	15
Depth below grade to water table	L_{WT}	(cm)	244 (488)

Modeling Parameter	Variable	Units	Value
Thickness of soil stratum A	h^A	(cm)	61 (305)
Thickness of soil stratum B	h^B	(cm)	183
Soil stratum directly above water table			B
SCS soil type directly above water table			C
Soil stratum A SCS soil type			SC
Stratum A soil dry bulk density	r_b^A	(g/cm ³)	1.63
Stratum A soil total porosity	n^A	(unitless)	0.39
Stratum A soil water-filled porosity	q_w^A	(cm ³ /cm ³)	0.2
Stratum B soil dry bulk density	r_b^B	(g/cm ³)	1.43
Stratum B soil total porosity	n^B	(unitless)	0.46
Stratum B soil water-filled porosity	q_w^B	(cm ³ /cm ³)	0.22

The values for the AES shed when different are shown in parentheses ().

Table 4. Building properties.

Modeling Parameter	Variable	Onsite Value	AES Admin. Value	AES Shed Value
Enclosed space floor thickness	L_{crack}	10	10	10
Soil-Building pressure differential	DP	40	40	40
Enclosed space floor length	L_B	1000	6096	610
Enclosed space floor width	W_B	1000	1524	366
Enclosed space floor height	H_B	244	244	244
Floor-Wall seam crack width	w	0.1	0.1	0.1
Indoor air exchange rate	ER	0.25	0.25	0.25

- Total Porosity for Stratum A (n^A): The porosity of 0.39 for sandy clay was used.
- Total Porosity for Stratum B (n^B): The porosity of 0.46 for clay was used.
- Water Filled Porosity for Stratum A: Average long-term volumetric soil moisture content that is typically a depth-averaged value for the appropriate soil stratum. Water filled porosity of 20% was used.
- Water Filled Porosity for Stratum B: The porosity for stratum B was 22%.
- Enclosed Space Floor Thickness (L_{crack}): A slab thickness of 4 inches or 10 cm was used. The model operates under the assumption that the floor is in contact with the underlying soil and is composed of impermeable concrete whether constructed as a basement floor or slab-on-grade.
- Soil-Building Pressure Differential: Because of wind effects on the structure, stack effects due to heating of the interior air, and unbalanced mechanical ventilation, a negative pressure with respect to the soil surface is generated within the structure. This pressure differential (ΔP) induces a flow of soil gas through the soil matrix and into the structure through cracks, gaps, and openings in the foundation. The effective range of values of (ΔP) is 0 to 20 Pascals (Loureiro et al., 1990; Eaton and Scott, 1984). Individual average values for wind effects and stack effects are approximately 2 Pa (Nazaroff et al., 1985;

Put and Meijer, 1989). Typical values for the combined effects of wind pressures and heating are 4 to 5 Pa (Loureiro et al., 1990; Grimsrud et al., 1983). A conservative default value of ΔP was therefore chosen to be 4 Pa (40 g/cm-s²). This default value of 40 g/cm-s² was used in the modeling effort.

- Building Dimensions:

Onsite Residence and Office Building

- Floor Length (L_B): 32.6 feet or 1,000 cm
- Floor Width (W_B): 32.6 feet or 1,000 cm
- Enclosed Space Height (H_B): 8 feet or 244 cm

Offsite AES Administration Building

- Floor Length (L_B): 200 feet or 6,096 cm
- Floor Width (W_B): 50 feet or 1,524 cm
- Enclosed Space Height (H_B): 8 feet or 244 cm

Offsite AES Shed

- Floor Length (L_B): 33 feet or 1,000 cm
- Floor Width (W_B): 33 feet or 1,000 cm
- Enclosed Space Height (H_B): 8 feet or 244 cm.

- Floor-wall seam crack (w): The Johnson and Ettinger model is based on a single-family house with a poured concrete basement floor and wall foundations, or constructed slab-on-grade in similar fashion. A gap is assumed to exist at the junction between the floor and the foundation along the perimeter of the floor. The gap exists as a result of building design or concrete shrinkage. This gap is assumed to be the only opening in the understructure of the house and therefore the only route for soil gas entry.
- Eaton and Scott (1984) reported typical open areas of joints between wall and floor slabs of residential structures in Canada of approximately 300 cm². Therefore, given the floor length and width of 1000 cm, a gap width (w) of 0.1 cm equates to a total gap area of 400 cm², which is reasonable given the findings of Eaton and Scott. This value of the gap width is also consistent with the typical value reported in Loureiro et al. (1990).

The default value of the floor-wall seam crack width of 0.1 cm was used in the modeling effort.

- Indoor air exchange rate (ER): The indoor air exchange rate is used, along with the building dimensions, to calculate the building ventilation rate. The default value of 0.25/hr was used for the residence. Note that this value represents lower 10th percentile of over 2000 residences studied and may overestimate the indoor concentrations for residences typical of warm climates.
- Chemical Properties: The chemical properties embedded in the *J&E* model are presented in Table 5 on CD.

Table 6 presents the exposure parameters for the resident and the industrial workers. The target risk (1×10^{-6}), target hazard index (1), carcinogenic averaging time (70 years), non-carcinogenic averaging time (30 years), exposure frequency (350 days per year) and exposure duration (30 years) were.

Table 6. Receptor exposure parameters.

Modeling Parameter	Variable	Units	Resident Value	Worker Value
Risk-Based risk for carcinogens	TR	(unitless)	$1E^{-06}$	$1E^{-06}$
Risk-Based hazard quotient for noncarcinogens	THQ	(unitless)	1	1
Averaging time for carcinogens	AT_C	(yrs)	70	70
Averaging time for noncarcinogens	AT_{NC}	(yrs)	30	25
Exposure duration	ED	(yrs)	30	25
Exposure frequency	EF	(days/yr)	350	83 ^a

^a The Exposure frequency equivalents are based on 24 hour exposure time per day. The exposure frequency for the industrial worker is 250 days per year; however the exposure time is 8 hours/day; therefore, the equivalent exposure frequency is $250 \times 8/24 = 83$ 24-hour days.

Modeling Results

The J&E modeling results are shown in Tables 7 to 9 on the attached compact disk (CD). The general and chemical-specific intermediate calculation results area are presented in Tables 7 and 8. The final chemical-specific intermediate results are provided in Table 9. The RBCs calculated for unit risk are provided in Table 10. The calculated final risks were provided previously in Table 1a to Table 1d for the different receptors.

Specifically, the infinite source building indoor air concentrations provided in Table 9 are converted to quantitative equivalent media concentrations (Table 10) using the unit risk factors (carcinogenic chemicals) and reference concentrations (non-carcinogenic chemicals), and the exposure parameters.

Also provided in Table 10, are the pure compound solubilities in groundwater, and soil saturation concentrations. The significance of these values is that they are the limiting factors; the maximum concentration that can be achieved in water or soil. If the calculated threshold concentration for a chemical is higher than its pure compound solubility or the soil saturation concentration, then it can be deduced that the chemical will not achieve a concentration in the media that would be of a concern for indoor inhalation. For example, acenaphthene threshold concentration is higher than its pure compound solubility and the chemical is denoted with "NOC" in the last column in Table 10. Similarly benzo(b)fluoranthene in soil will reach the maximum concentration before the threshold concentration can be achieved. This information is useful in determining the remediation goals that they may not exceed the pure compound solubility or the soil saturation points.

Table 1 indicates that carcinogenic risk primarily arises from benzene and ethylbenzene, and non-carcinogenic risk primarily arises from benzene and m & p-xylenes.

Uncertainty, Limitations and Assumptions

The following represent the major assumptions and limitations of the *J&E* model (USEPA, 2003).

1. Contaminant vapors enter the structure primarily through cracks and openings in the walls and foundation.
2. Convective transport occurs primarily within the building zone of influence and vapor velocities decrease rapidly with increasing distance from the structure.
3. Diffusion dominates vapor transport between the source of contamination and the building zone of influence.
4. All vapors originating from below the building will enter the building unless the floors and walls are perfect vapor barriers.
5. All soil properties in any horizontal plane are homogeneous.
6. The contaminant is homogeneously distributed within the zone of contamination.
7. The areal extent of contamination is greater than that of the building floor in contact with the soil.
8. Vapor transport occurs in the absence of convective water movement within the soil column (i.e., evaporation or infiltration), and in the absence of mechanical dispersion.
9. The model does not account for transformation processes (e.g., biodegradation, hydrolysis, etc.).
10. The soil layer in contact with the structure floor and walls is isotropic with respect to permeability.

Additional assumptions specific to the application of the model for the site are contained in the *User's Guide for the Johnson and Ettinger (1991) Model for Subsurface Vapor Intrusion into Buildings* (USEPA, 2003).

In the areas neighboring the site, many homes are built on concrete piers; however, it has been conservatively assumed that the standard home is constructed as slab on grade. The implication of this assumption is the vapors dissipate inside the house instead of outside the house. In addition, the windows of the houses consist of insect screens and louvers (i.e., no glass windows observed), likely resulting in a higher air exchange rate than 0.25 per hour. A higher air exchange rate would imply more vigorous flushing of the contaminants resulting in lower air concentrations inside the house.

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